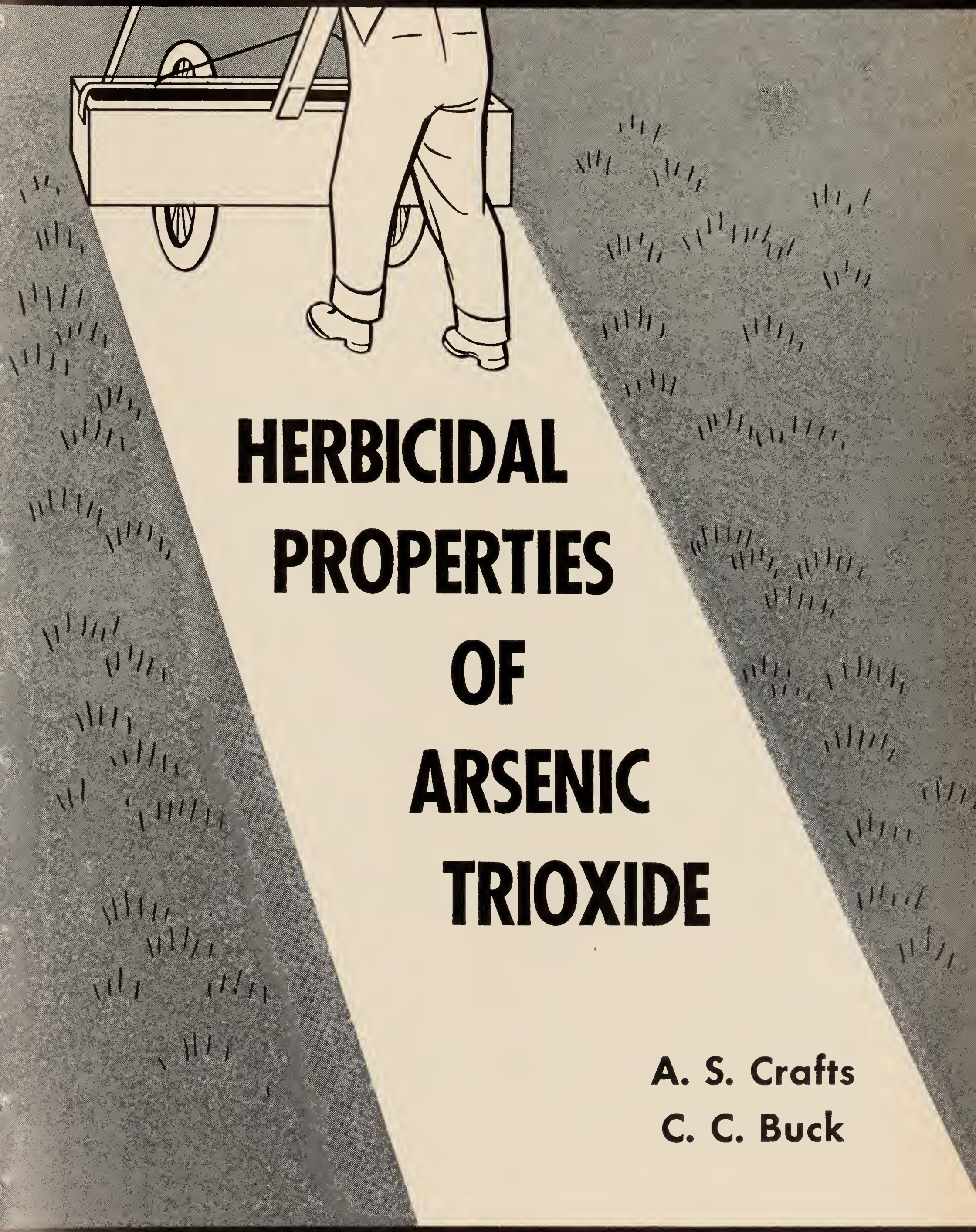
Division of Agricultural Sciences
UNIVERSITY OF CALIFORNIA



HERBICIDAL PROPERTIES OF ARSENIC TRIOXIDE

A. S. Crafts
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CALIFORNIA AGRICULTURAL EXPERIMENT STATION

BULLETIN 739

HERBICIDAL

Pushcart applicator used for spreading arsenic trioxide on some of the tests described in this bulletin. This particular applicator was designed in the University of California's Department of Agricultural Engineering at Davis.

WEED CONTROL THROUGH PREVENTION can be achieved by chemical soil sterilization.

EFFECTIVE, LONG-LASTING, SAFE, AND ECONOMICAL, arsenic trioxide (white arsenic) has proved to be a satisfactory means of soil sterilization. On farming lands, along fence lines, ditchbanks, railroad ballast, and firebreaks, around airfields and construction or parking areas—wherever weeds are a threat to efficient operation, arsenic trioxide will destroy growth and prevent recurrence for periods of 5 to 10 years.

ARSENIC TRIOXIDE HAS THESE ADVANTAGES over the soluble forms of arsenic—

Not attractive to livestock, it is less hazardous.

Low in solubility, it is persistent in the soil.

Three forms—the original dust, a dustless powder, and pellets—make it adaptable to different kinds of terrain. It can be applied either by hand or machine depending on the terrain.

This bulletin tells how 80 California soils responded to treatment in greenhouse tests, small field plots, and large-scale operations.

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PROPERTIES of ARSENIC TRIOXIDE

A. S. CRAFTS

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THE PROBLEM . . .

Before arsenic trioxide could replace the more hazardous sodium arsenite as a soil sterilant, years of experimentation were needed to find out exactly how this chemical behaved in soil and how to handle it in field-scale operations. Here are the findings and recommendations concerning its use.[1]

WEED CONTROL by chemical means has advanced rapidly since it was found that pesticides could be economically applied in quantity for large-scale control operations. Chemical methods, long viewed as expedients, have proved practical and economical for field-scale use on millions of acres in this and other countries. They have increased the possibility of waging total war on agricultural and industrial plant pests.

Chemical soil sterilization is preventive weed control and, as in the case of medicine, prevention is better than cure. As weed control becomes more highly mechanized and as the use of chemicals increases, emphasis is bound to shift from seasonal treatment to lasting prevention. In this phase arsenic sterilization will occupy an important position.[2]

Arsenic is still the most practical and persistent material for permanent soil sterilization, and for this purpose arsenic trioxide (white arsenic) has been found to have distinct advantages over the soluble forms. Apparently not attractive to livestock, it is less hazardous to use. It is low in solubility and is, therefore, persistent. It may be applied in the dry form either as the original dust, as a dustless powder, or in the form of pellets. For large-scale application the carrier-free dry form is most economical; for treating railroad ballast the pellets have distinct advantages because they gravitate into the crevices, resisting displacement by wind and concentrating in the regions where seeds germinate.

Arsenic trioxide, commonly known as white arsenic, is a white, finely crytalline substance having a density of 3.75. It is produced as a by-product in the smelting of copper ores, and at times it has accumulated in huge surpluses. It is used as the primary source material in the production of sodium arsenite

[1] Research reported in this bulletin was financed by the American Smelting and Refining Company and conducted by the Botany Department, University of California, Davis, California. Work on firebreaks was done by the California Forest and Range Experiment Station, Forest Service, U. S. Department of Agriculture.

[2] Soil sterilization by means of arsenic has been described by Crafts (1935*b*, *c*); Crafts and Cleary (1936); Crafts (1939*b*); Crafts and Rosenfels (1939); Crafts, Bruce, and Raynor (1941); Rosenfels and Crafts (1939); Robbins, Crafts and Raynor (1942).

(weed-killer), calcium arsenate dust used in cotton bollworm control, and lead arsenate used against codling moth of pome fruits. Sodium and calcium arsenites are used as insecticides and fungicides, and Paris green is a mixed salt containing arsenic. There are other uses in agriculture and industry, but the above have in the past consumed the bulk of the arsenic produced in this country.

With the introduction of DDT and many other new organic insecticides and the substitution of 2,4-D, borax, chlorates, and other chemicals for sodium arsenite as a weed-killer, it seemed possible that arsenic would again be in surplus supply. Realizing the potential large-scale use of arsenic trioxide as a soil sterilant, scientists began work in 1949 to clarify some of the problems involved and to amplify our general knowledge of the behavior of this chemical in the soil.

Arsenic is extremely toxic to plants; it kills through contact with either foliage or roots. Applied to the tops of plants in soluble form (sodium arsenite solution), it causes rapid death of contacted tissues; any residue falling on the soil will cause injury to plant roots if carried into the zone of absorption.

Applied to the soil in soluble form, arsenic may be leached into the root zone where it exerts its toxic action. However, on a concentration basis, it is much less effective applied through the soil than it is applied in culture solution. This indicates that its toxicity to plant roots is greatly reduced through contact with the soil. Arsenic, like phosphate, is fixed by the soil, and much of the fixed arsenic is rendered unavailable to plants; a small proportion remains immobile but available. It is this fraction that is important in soil sterilization.

Work with 80 California soils proved that arsenic toxicity is determined largely by textural grade as this character relates to colloidal content. Kaolinitic clays are particularly effective in fixing arsenic in a form unavailable to plants.

Recommendations for use of arsenic trioxide in soil sterilization in California call for application during the winter months when rainfall or snows carry the chemical into the topsoil. The object of this recommendation is twofold: (1) to get the arsenic into the moist soil so it will start dissolving; (2) to make the application when there is little or no vegetation on the soil, thus minimizing the poison hazard. All applied arsenic is subject to leaching by rains or melting snow; however, arsenic resists leaching and is washed from the soil only by large quantities of water not normally falling as precipitation. Arsenic applied as dry crystalline trioxide is less readily leached from the soil than arsenic applied in solution.

An important objection to the use of arsenic in weed control has been its great poison hazard. This is particularly true of soluble arsenic, which is not only poisonous but also attractive to livestock. Arsenic trioxide apparently has no such attraction, and its use has proved safe even in areas in which livestock are grazing. At the California Forest and Range Experiment Station arsenic trioxide was spread on firebreaks in open range country where livestock and wildlife were present. The animals were curious; they came up and sniffed the arsenic but did not taste it.

The present program is aimed at developing the use of arsenic trioxide for soil sterilization along railroads, irrigation ditchbanks, fence lines, rights-of-way, airfields, firebreaks, and other places where all weed growth is undesirable.

THE STUDIES . . .

Three methods were used to study the herbicidal properties of arsenic trioxide: (1) greenhouse tests on arsenic toxicity in soils, using the concentration series; (2) field plots to find the effects of arsenic application on various weeds growing in several soils and exposed to differing environmental conditions; and (3) applications on a field scale to an airfield, to a series of structures on a large irrigation system, and to firebreaks in forest and range areas.

Greenhouse tests

The experiment. The toxicity studies follow the pattern that has been used in the studies on sodium arsenite (Crafts, 1935*b*; Crafts and Cleary, 1936; Crafts and Rosenfels, 1939), sodium chlorate (Crafts, 1935*a, b, c;* Crafts, 1939*a, b;* Rosenfels and Crafts, 1939), borax (Crafts and Raynor, 1936; Crafts, 1939*b*), and other herbicidal chemicals. Small pot cultures were set up in series, No. 2 cans (unperforated) serving as containers. The concentration series used in these tests runs as follows: 0, 40, 80, 140, 220, 340, 490, 680, 920, 1,220, 1,590, 2,040, 2,580, 3,220, 3,920, and 4,840 ppm As_2O_3 in air-dry soil. Weighed amounts of arsenic trioxide were mixed with 500-gram lots of soils by rotation in closed jars on a soil mixer. The dry mixtures were moistened to field capacity by adding water to weight. The cultures were planted using 13 Kanota oats per can; one week after germination they were thinned to 10 plants per can. They were harvested 30 days after planting, and the green weight and average height for each culture were recorded. All series were run in triplicate. Figures 1 and 2 show some of the cultures at harvest time.

In addition to the straight toxicity series, test series were run in which periods of 2, 3, 5, 7, 9, and 16 days were

Fig. 1. Toxicity of white arsenic to crop #1 in two California soils; left, Sierra fine sandy loam, and right, Aiken clay loam. Toxicity is highest in sandy soils. In both series the cultures on the left are controls, the center cultures have 490 ppm in the air-dry soil, the right-hand cultures 1,220 ppm.

Fig. 2. Left, toxicity of white arsenic to crop #1 in Hanford loam, and right, Yolo clay loam. Left, (in each photo) controls; center, 490 ppm; right, 1,220 ppm.

allowed to pass between moistening the cultures and planting the oats. This was to allow time for solution of the arsenic trioxide to take place. Yolo clay loam was used in this experiment.

Two toxicity series were established in which a wetting agent (Tenlo 400) was included in the moistening water. These were run in Hanford fine sandy loam and Yolo clay loam and were cropped for three 30-day periods with intervening 30-day drying periods.

In field-plot tests the dustiness of the dry arsenic proved to be a nuisance and a hazard to the operator making the applications. To avoid this and to minimize blowing of the arsenic where applications were being made to railroad ballast, about a ton of arsenic trioxide was pelleted for experimental application. For similar purposes a small quantity of a granular form of As_2O_3 was supplied by the American Smelting and Refining Company. Greenhouse trials were run using plain arsenic trioxide dust, pelleted arsenic trioxide, and the granular form.

As an alternative method to reduce dustiness, liquid wetting agents were added to the dry dust. This proved very effective, and samples of several such mixtures were supplied by the California Spray Chemical Company for testing under greenhouse conditions. Data on these tests, which were cropped for seven successive periods in Yolo fine sandy loam, are given.

Table 1 characterizes the soils that were used in the greenhouse tests.

The results. Data on six runs of the toxicity series are presented in figures 3 to 12. Figure 13 presents the results of similar tests with sodium arsenite in a group of 80 California soils (Crafts and Rosenfels, 1939). A comparison of the results shows that in the first run toxicity is much lower with arsenic trioxide than with sodium arsenite. This is to be expected because arsenic trioxide is low in solubility and requires time to dissolve in sufficient quantity to provide a lethal concentration in the soil. Though somewhat less apparent than when soluble arsenic is used, the relation between toxicity and textural grade is evident in these results.

By the time the second run was harvested, toxicity had increased appreciably in each soil. This is in line with results in the field where it has been ob-

Table 1. Characteristics of California Soils Used in Toxicity Tests

Soil type	Origin	Mode of formation	Stage of development	Color	Reaction
Aiken clay loam	Basic igneous	Primary	Semimature	Red	Slightly acid
Egbert loam	Mixed organic	Secondary alluvial	Immature	Dark gray	Slightly acid
Hanford fine sandy loam	Acid igneous	Secondary alluvial	Recent	Light brown	Neutral
Hanford loam	Acid igneous	Secondary alluvial	Recent	Light brown	Neutral
Rocklin fine sandy loam	Acid igneous	Secondary alluvial	Mature	Brown-red	Slightly acid
Sierra fine sandy loam	Acid igneous	Primary alluvial	Semimature	Brown-red	Mod. acid
Stockton adobe clay	Basic igneous	Secondary alluvial	Mature	Gray-black	Basic
Willows adobe clay	Sedimentary	Secondary alluvial	Semimature	Dark brown	Neutral
Yolo fine sandy loam	Sedimentary	Secondary alluvial	Recent	Brown	Neutral
Yolo clay loam	Sedimentary	Secondary alluvial	Recent	Brown	Neutral

served that sterility does not reach a practical level in medium to heavy soils until the second season. In light sandy soils sterility may be very evident the first season, particularly on soils low in fertility.

In most of the soils maximum toxicity is not attained until the third run. Sierra fine sandy loam is the only exception; in this soil the second run exhibited maximum toxicity. This is explained by the coarse granitic nature of the sand in this soil.

Runs number four and five were not significantly different from run number three in these soils, but in several soils run number six showed loss of toxicity. This is understandable in the case of Stockton adobe clay and Aiken clay loam on the basis of fixation by clay colloids, but in Sierra and Rocklin fine sandy loam this reasoning does not apply. Kaolinitic clays in these soils may account for the lowered availability of the arsenic.

Figs. 3 to 12 show the relation of crop yield to the concentration of white arsenic in the various soils tested. The graphs for these figures appear on the following pages.

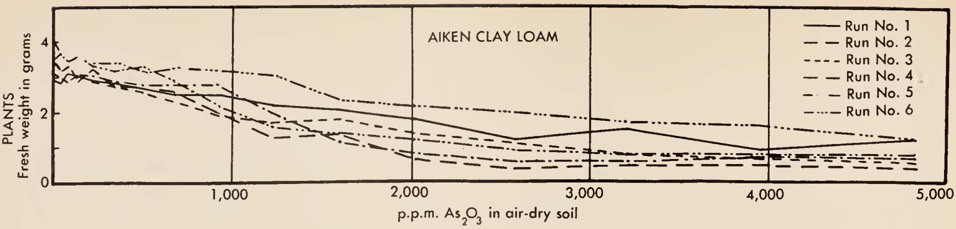


Fig. 3

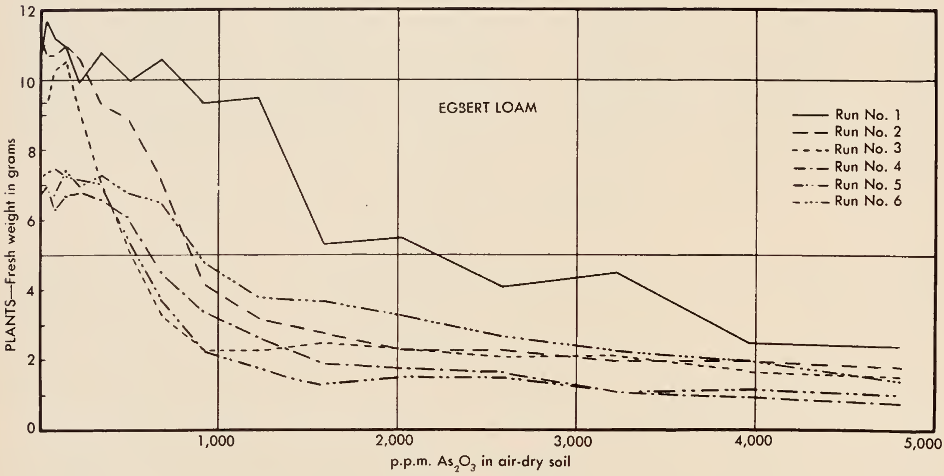


Fig. 4

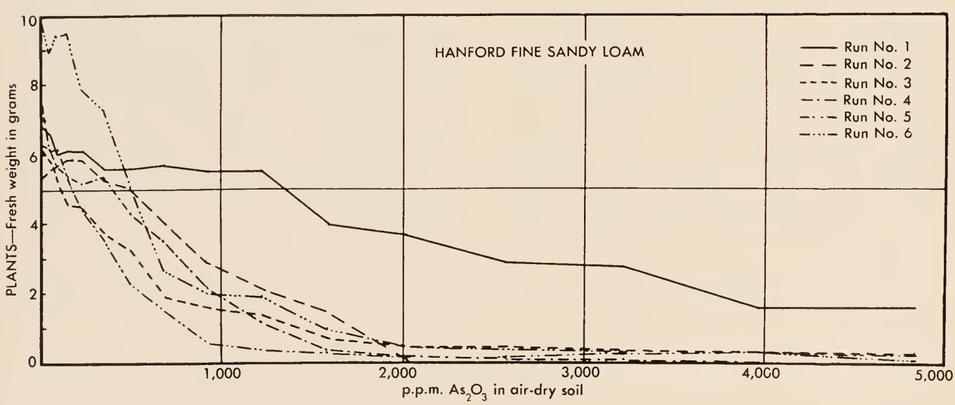


Fig. 5

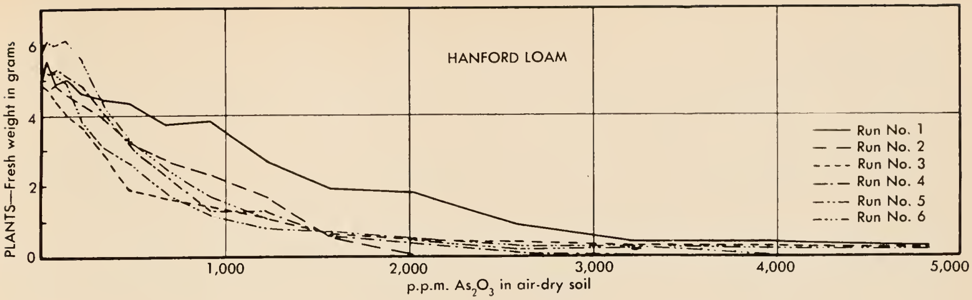
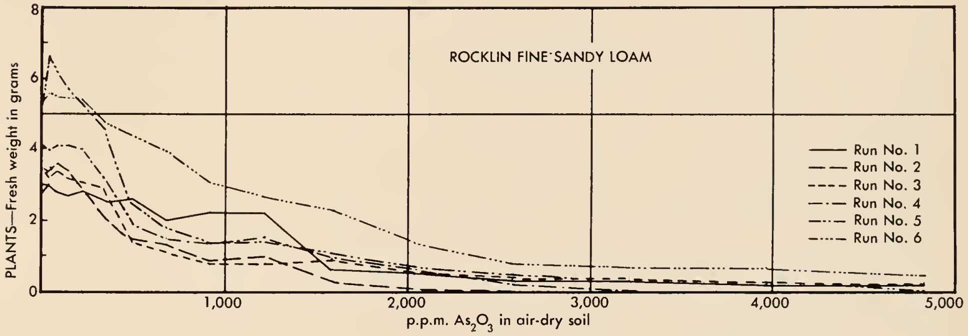


Fig. 6



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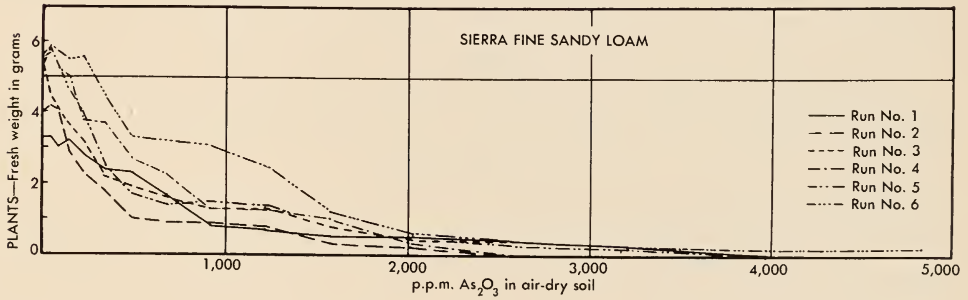

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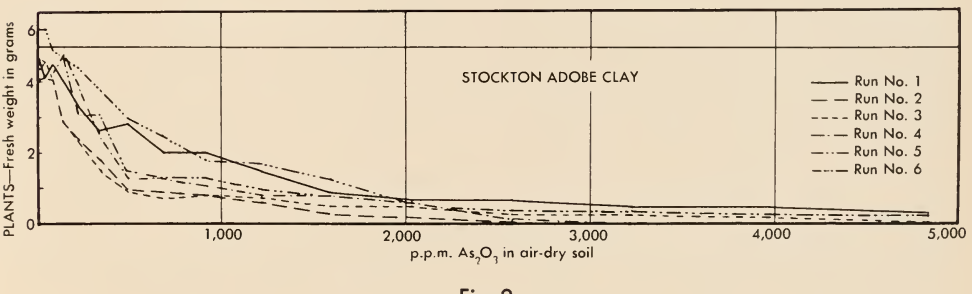

Fig. 9

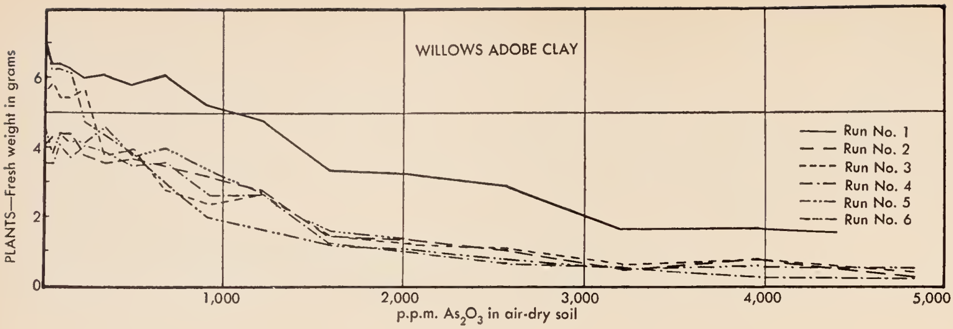

Fig. 10

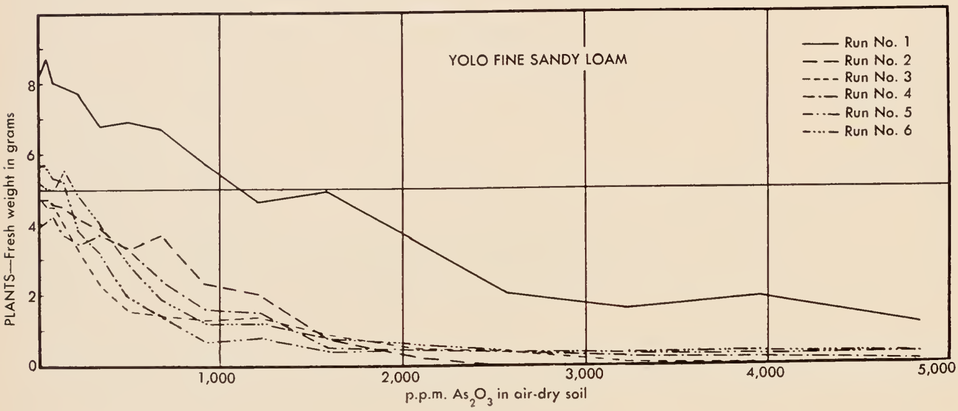

Fig. 11

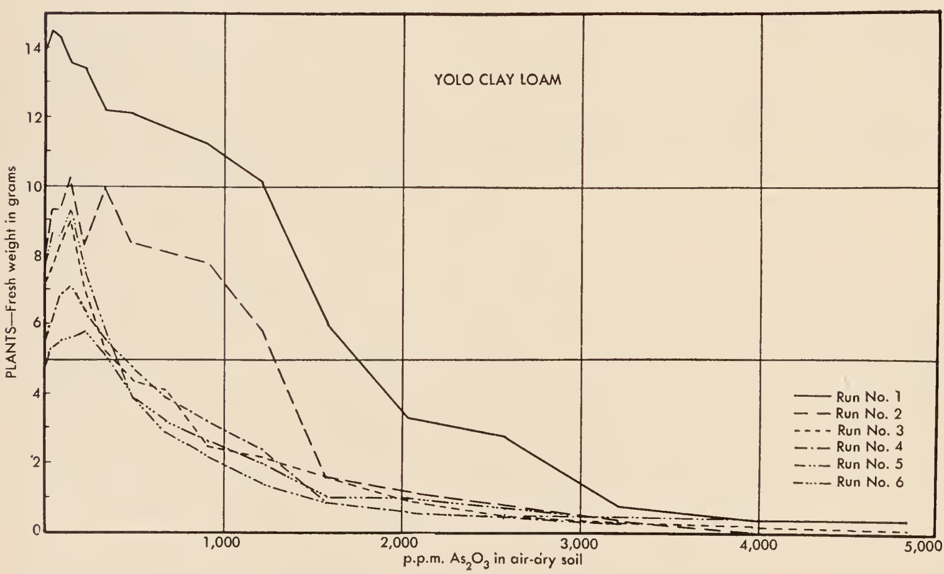

Fig. 12

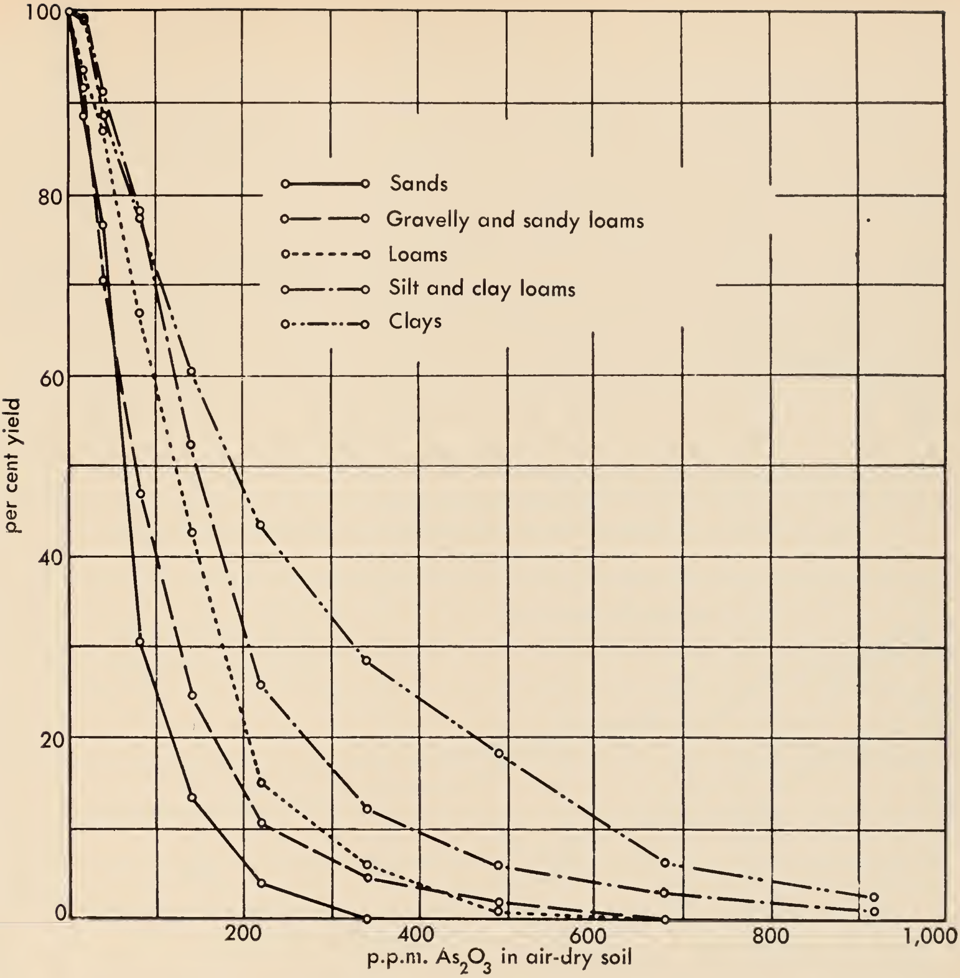

Fig. 13. The relation between textural grade and arsenic toxicity from the summaried results of toxicity tests in 80 California soils. (From Crafts and Rosenfels, HILGARDIA, Vol. 12, Calif. Agr. Exp. Sta.)

Figure 14 presents the data on the experiment in which periods of from 2 to 16 days were allowed between moistening the cultures and planting them. It is apparent from the values that periods up to and including 9 days resulted in no significant increase in toxicity. Figure 14 shows three curves: (1) the first run in Yolo clay loam converted to a control value of 11.2, (2) a curve made by combining the values for the 2-, 3-, 5-, 7-, and 9-day delay periods, and (3) a curve for the 16-day delay period. Since the culture series ran to only 1,220 p.p.m., the curves do not go to the base line. However, the trends are clearly shown, and there is no doubt that the 16-day period has been long enough to allow appreciable solution of the arsenic trioxide in the soil.

Hanford fine sandy loam and Yolo clay loam were used for the experiment with wetting agent (Tenlo 400). Figures 15 and 16 show the results. In the Hanford soil the differences were hardly significant; in Yolo clay loam the tox-

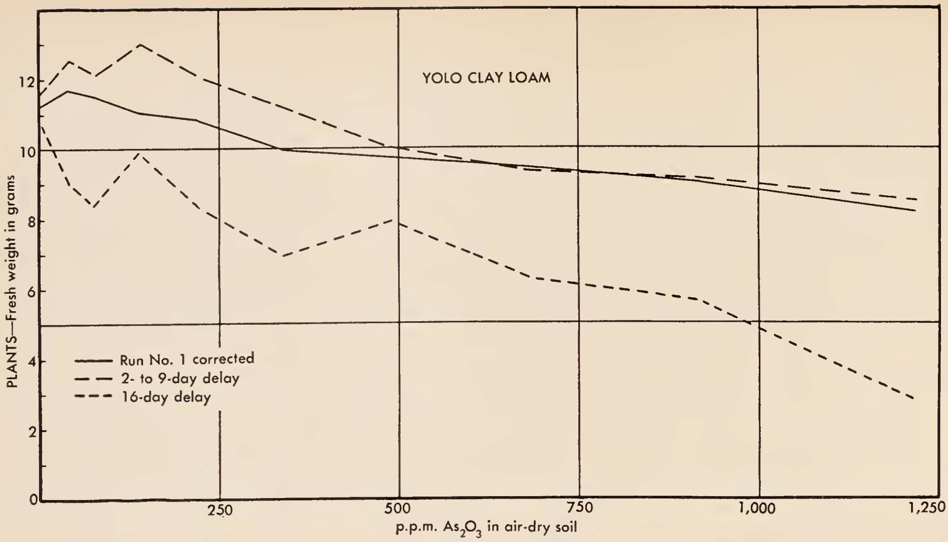

Fig. 14. Toxicity of white arsenic in Yolo clay loam as related to solution time for the applied arsenic.

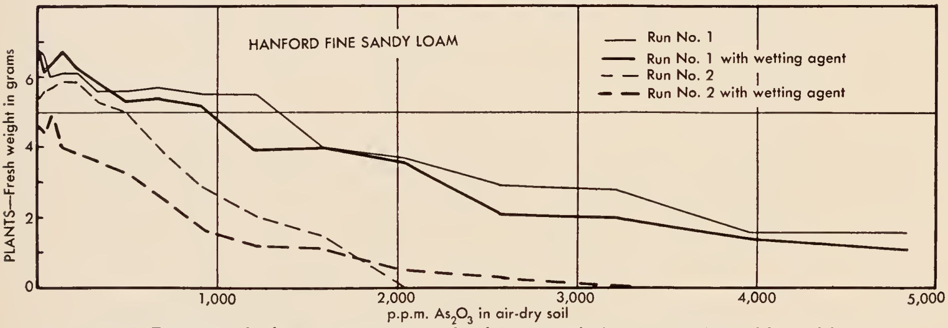

Fig. 15. Toxicity of white arsenic in Hanford fine sandy loam as affected by addition of a wetting agent (Tenlo 400).

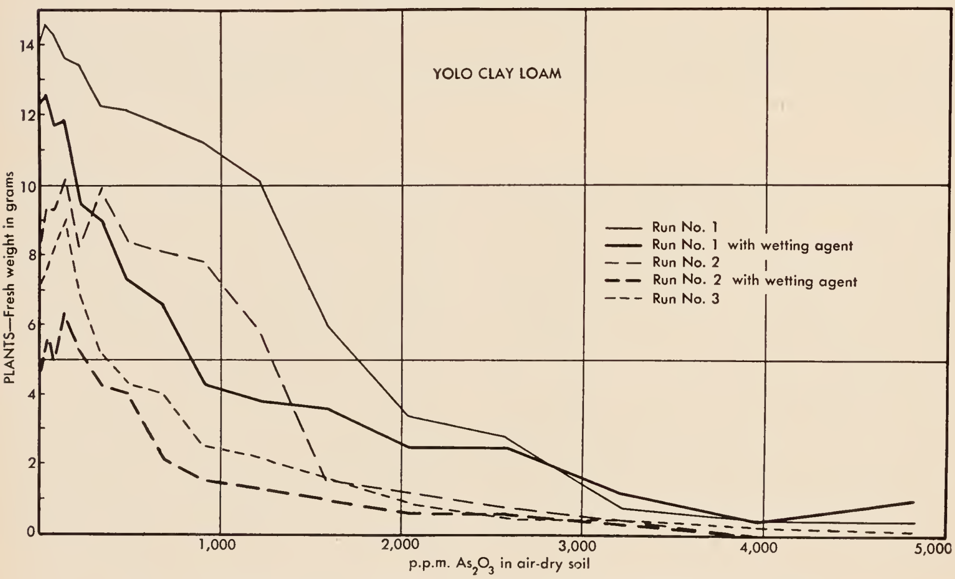

Fig. 16. Toxicity of white arsenic in Yolo clay loam as affected by addition of a wetting agent (Tenlo 400).

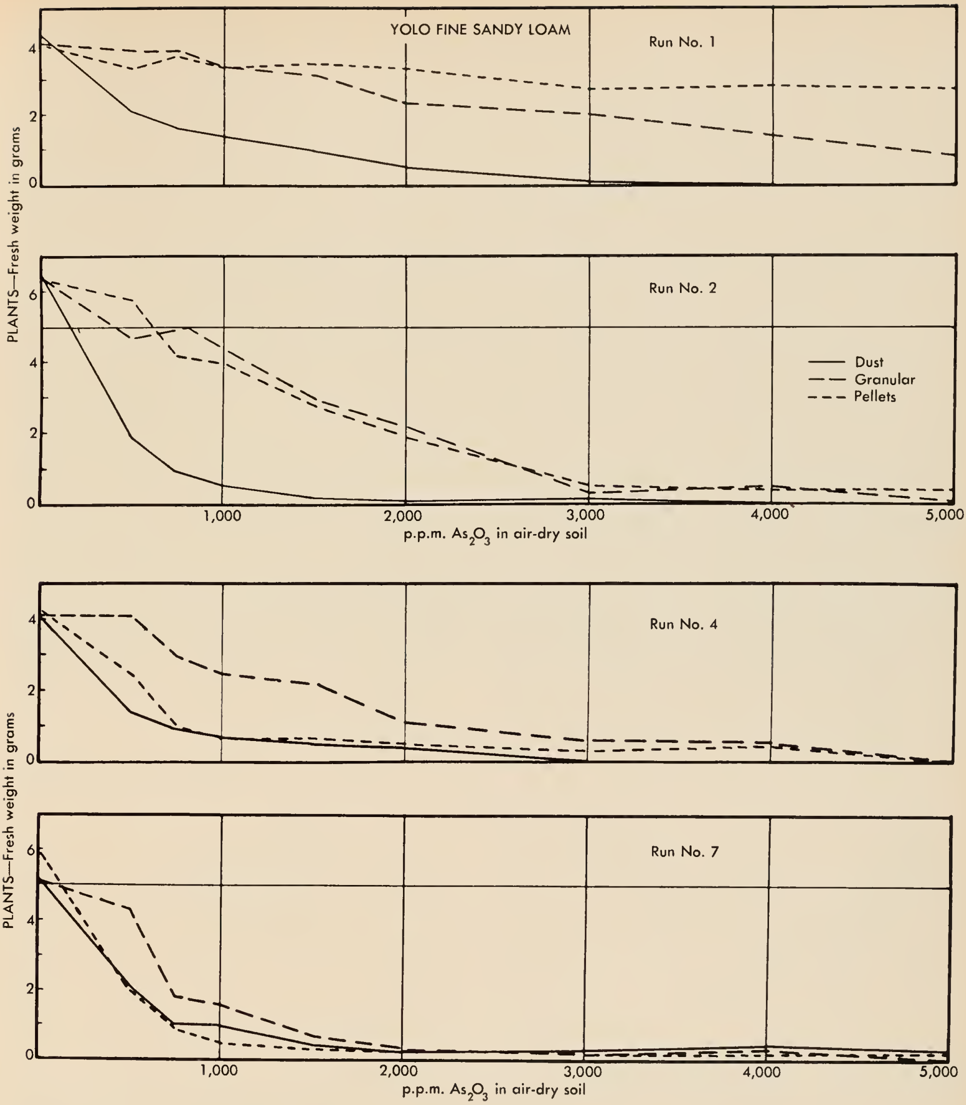

Fig. 17. Toxicity of white arsenic in Yolo fine sandy loam as related to the form applied. Four runs with dust, pellets, and a granular glassy form.

icity of the arsenic was materially increased, run number one with wetting agent approaching run number two without, and run number two with wetting agent being more effective than run number three without. Whether the effect is due entirely to greater solution of the arsenic or to a more complex response involving the wetting agent as an inhibitor of fixation cannot be determined from these simple tests. They do indicate, however, that inclusion of a wetting agent to reduce dustiness may also increase toxicity during the first year after application.

When the question of pelleting arsenic trioxide was raised, representatives of the American Smelting and Refining Company suggested the possible alternative of using the granular

arsenic that is produced along with the dust in the smelting process. Trials were run with this granular form and with some pellets that had been produced experimentally, the dust serving as a control. Figure 17 presents the results of this test in Yolo fine sandy loam. Toxicity of the granular form and the pellets was very low in the first run; in the second run it was considerably higher for each. In the fourth and seventh runs the pellets were as toxic as the dust form, and by the seventh run the granular form was approaching the other two.

Granular arsenic is evidently very low in solubility; even by the seventh run it had released only as much soluble arsenic as was available from the dust during the first run. Arsenic in the pellets was somewhat slower to dissolve than the dust. Furthermore, the pellets were dispersed through the soil mass in definite restricted locations during the first run, and the roots of the oat plants could grow through the unaffected soil between them. By the second run, arsenic from the pellets was somewhat more thoroughly mixed with the soil but still not completely. Possibly also the binder used in the pellets restricted solution. That this is not serious in field applications is indicated by the high toxicity of the pellets in the second year of treatment. In general, the pellet applications were as effective as, or in some cases more effective than, dust applications on railroad ballast. In some situations this might have reflected the greater stability of the pelleted form with respect to wind action from passing trains.

While the above trials were being conducted, one company, interested in the sale of arsenic trioxide as a soil sterilant, submitted four samples that had been formulated with different wetting agents to produce dustless products for commercial application.

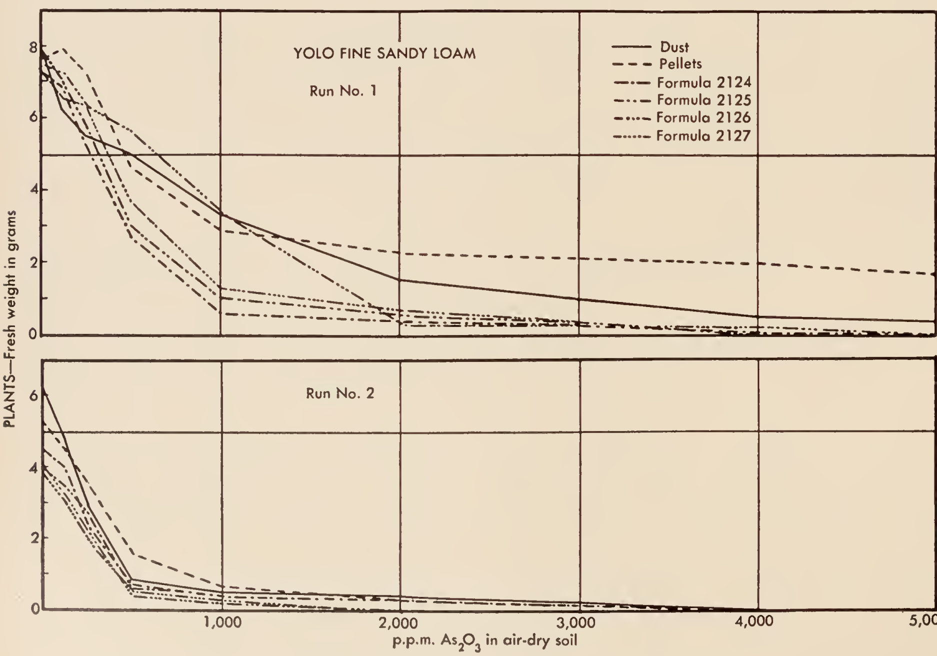

Fig. 18. Toxicity of white arsenic in Yolo fine sandy loam as related to formulation. A comparison of dust, pellets, and four formulations involving mixtures of commercial surfactants with arsenic dust.

Fig. 19. Sterilization plots seven years after treatment with arsenic trioxide. The heavy lines mark the borders of plot areas in which applications were 8, 12, and 16 pounds per square rod. Vegetation has returned to the right-hand portions of the plots where road maintenance machinery has disturbed the soil.

Figure 18 gives the data for runs number one and two with these materials. Lot number 2,126 was little better than the dust during run number one; lots 2,124, 2,125, and 2,127 were considerably better. By the second run all formulations and dust and pellets gave comparable results. These tests indicate that considerable time can be gained in obtaining sterilization with arsenic trioxide by incorporating a wetting agent. Evidently, however, these agents differ somewhat in their solubilizing power.

During the time the above tests were being made, the new organic soil sterilant, p-chlorophenyl 1, 1, dimethyl urea (CMU), was presented for trial. Combinations of arsenic trioxide and CMU were tried in hope of finding a mixture that would be effective in the year of application. These tests proved that there is little or no antagonism between arsenic trioxide and CMU, that the effects were additive, and that such a combination is very toxic, provides rapid sterilization, is effective the first year, and lasts as long as the arsenic dosage determines.

Plot tests

The experiment. Plot tests with arsenic trioxide were established at Davis in October, 1931 (Crafts, Bruce and Raynor, 1941, table 1). Since then many hundreds of trials have been made. The object was to establish the dosage requirements under widely different climatic conditions and to learn more about handling the chemical in the field.

Dosage requirements under various climatic conditions were studied by establishing plots on railroad main lines and sidetracks at various locations from Marysville on the north to Lodi on the south. To include altitude as a factor, series of plots were established at Rose-

Fig. 20. Left, plots treated with white arsenic. Released from competition with annual weeds, Elymus triticoides, a deep-rooted perennial grass, has flourished and now almost completely occupies the area. A readily leached soil sterilant is required in addition to white arsenic in this situation. Right, ballast and tow path sterilized with white arsenic. A patch of E. triticoides is shown encroaching on the tow path on the left of the track.

ville, New England Mills, Colfax, Towle Station, Yuba Pass, Soda Springs, Truckee, California, and Verdi, Nevada. On this latter group of plots arsenic dust and arsenic pellets were compared. A pushcart applicator was used to spread the chemical. Three years' results have been observed on these plots.

The results. Figure 19 shows one of the early plots established for a previous study (Crafts, Bruce, and Raynor, 1941). The object of the plot studies in the present project was to improve application methods and to gain practical experience in handling arsenic trioxide in the field. The first series was treated in February, 1950, and consisted of 16 plots, each two square rods in area, located in pairs. One had a west exposure and extended 32 feet from the tracks down into the borrow pit of the Southern Pacific Railroad where the latter traverses the Armstrong Tract of the University of California south of Davis. The second plot of each pair faced east on the same right-of-way. Treatments included applications of 2, 4, 6, 8, 10, 14, 16, and 20 pounds per square rod. The chemical was applied when the vegetation was from 6 to 12 inches high. A second series of plots was treated with applications of 2, 4, 6, 8, 14, and 20 pounds per square rod in March, 1950, when the vegetation was 10 to 14 inches high. There was little visible effect on any of these plots during the season of treatment.

Examination of these plots in the early summer of 1951 and again in 1952 proved that the arsenic application required to control annuals on this Yolo loam soil on sloping terrain was 10 pounds per square rod or more. And where the deep-rooted grass *Elymus triticoides* was present, it thrived and completely covered the treated plots. Figure 20 shows such a plot. This stresses the fact noted in previous studies (Crafts, Bruce, and Raynor, 1942; Raynor, 1937) that arsenic trioxide is not effective against perennial weeds and should not be used alone in situations where such weeds occur. Also noted was the fact that sloping soil is more difficult to sterilize than level soil. This has a practical bearing in many situations where soil sterilization is desired.

In November, 1950, a series of arsenic plots was established on the Southern Pacific Railroad along the main line

south of Davis. A second series was treated in December, 1950. In each, arsenic trioxide, both in dust and pellet form, was applied with a three-foot pushcart applicator, designed and built by Norman Akesson of the Agricultural Engineering Department at Davis (see page 2). Table 2 presents the readings on these plots, taken in May of 1951 and 1952. It is evident that the 1952 readings represent a more complete sterilization than those of 1951. This is typical of arsenic trioxide and confirms the greenhouse tests where maximum toxicity was not attained until the third cropping on some soils.

A second conclusion that may be drawn from the data in table 2 is that the pelleted arsenic was somewhat more effective than the dust. These plots were on the main line over which many trains passed daily. It was noted that the passage of trains during and immediately after the applications caused the arsenic

Table 2. Results of Soil Sterilization with Arsenic Trioxide on Railroad Plots (Ballast and Tow Path) South of Davis.* Application by Mechanical Applicator (Three-foot Pushcart). Notes taken in May, 1951 and 1952

Arsenic form and date of application	Application	Percentage of control	
		1951	1952
	pounds per acre		
Dust (Oct. 28, 1950)	500	30	60
	750	45	75
	1,000	60	85
	1,280	65	85
	1,500	60	90
	1,750	65	90
	2,000	75	98
Pellets (Oct. 28, 1950)	500	35	70
	750	50	80
	1,000	60	90
	1,280	60	95
	1,500	70	98
	1,750	65	95
	2,000	75	98
Dust (Dec. 10, 1950)	750	25	25
	1,000	45	75
	1,280	65	85
	1,500	70	80
	1,750	70	90
	2,000	90	90
Pellets (Dec. 10, 1950)	750	50	80
	1,000	70	90
	1,280	80	90
	1,500	80	90
	1,750	90	98
	2,000	90	99

* Plots 9' x 100'.

dust to rise and blow in swirling currents, some actually being blown off the plots by each passing train. This did not take place where pellets were used. In fact, close inspection proved that these tended to settle in crevices between the rock ballast and so to concentrate in the regions where seeds tended to germinate. This is a distinct advantage.

In November, 1950, a series of plots was established on the Western Pacific Railroad between Sacramento and Lodi. These are reported in table 3. Most of the plots were located on mounds around signal towers. These mounds are graveled or paved with crushed rock and are difficult to keep clean by hoeing. By 1952 the arsenic had done an excellent job of sterilization against annual weeds, but in many cases perennials persisted and where they were not killed by spraying they tended to invade the areas. Of the annual weeds that were able to gain entrance to the areas, yellow star thistle (*Centaurea solstitiales*) and knotweed (*Polygonum aviculare*) were the two most serious.

During December, 1950, and January, 1951, additional plots were established near Woodland in Yolo County and at Bahia Station in Solano County, all alongside tracks and spur tracks of the Southern Pacific Railroad Company. Table 4 presents the readings on these plots, and figures 21, 22, and 23 show the results.

A final series of plots on the Southern Pacific main line was established in December, 1950, and January, 1951. These plots were located from Roseville through the Sierra to Verdi, Nevada. They covered wide ranges in natural precipitation and altitude and included areas where snow is prevalent throughout the winter. These plots are reported in table 5. Figure 24 shows the treated

Table 3. Results of Soil Sterilization with Arsenic Trioxide Dust, Applied November 3, 1950, on Railroad Plots between Sacramento and Lodi. Application by Hand Spreading. Notes Taken in May, 1951 and 1952

Size of plot	Location	Application	Percentage cf control		Notes
			1951	1952	
feet		pounds per acre			
150 x 12 25 x 25	W.P. RR. at Alberta	2,000 2,000	80 75	98 98	Winter annuals all dead; yellow star thistle encroaching
25 x 25 100 x 6 25 x 25	W.P. RR. at Kingdom Sta.	2,000 2,000 2,000	65 80 75	75 95 90	Yellow star thistle encroaching; also perennial weeds.
300 x 6	Terminous road	2,000	75	95	Yellow star and mayweed
25 x 25 25 x 20	Thornton, Crossing 113.3	2,000 1,000	75 50	98 95	Knotweed and yellow star encroaching
25 x 25	South of Franklin, Crossing 118.6	2,000	75	95	Yellow star encroaching
25 x 25	Franklin	1,000	90	98	Poppies and milkweed encroaching

Table 4. Results of Soil Sterilization with Arsenic Trioxide on Railroad Plots near Woodland and Benicia. Application by Mechanical Applicator (Three-foot Pushcart). Notes Taken in May, 1951 and 1952

Arsenic form	Date	Plot size	Location	Application	Percentage of control		Notes
					1951	1952	
		feet		pounds per acre			
Dust	Dec. 28, 1950	400 x 12	Sugar yard	1,200	50	75	Sidetrack with many beets on the ground
Dust		400 x 4	Spreckels	1,200	40	50	
Dust		200 x 8	Sugar Co.	1,200	40	50	
Dust		200 x 8	Woodland	1,200	30	50	
Dust	Dec. 28, 1950	300 x 6	Spreckels Plant, Woodland	1,600	75	90	Spur track No. 1
Dust		250 x 6		1,000	80	90	Spur track No. 2
Dust		300 x 6		1,000	75	90	Spur track No. 3
Pellets		300 x 6		1,200	70	80	Main track
Dust		300 x 6		1,200	60	75	Main track
Pellets	Dec. 27, 1950	1,100 x 6	North of Woodland	1,200	80	99	Heavily gravelled sidetrack
Dust		40 x 9		1,200	80	99	
Dust	Dec. 27, 1950	1,300 x 12	South of Woodland	1,200	85	100	Loading area
Dust	Jan. 10, 1951	50 x 50	Bahia	1,500	80	99	Gravelled yard
Dust		300 x 6		1,500	85	99	Ballast

strips at Truckee, Calif. The data bear out the observations that sterilization is better after the third winter season, that the pellets in general are superior to dust, and that annual weeds succumb to the treatment but perennials usually survive. The notably poor results at Verdi in May, 1951, probably reflect the low total precipitation in this area. These contrast with the generally better results on the wetter west slope.

In conclusion it should be emphasized that the data presented in tables 2 to 5 relate only to annual weeds. If readings on perennial weeds or total weed growth had been reported, they would be different. This proves that one chemical cannot be expected to stay in the topsoil and control seedlings and annual weeds, and at the same time leach into the lower soil horizons and act on the roots of perennials. Wherever annuals and perennials occur, soil sterilization involves two separate processes and, under most conditions, requires two chemicals. One of these, because of fixation or low solubility, should remain active in the surface soil, while the other moves into lower levels to handle the deeper-rooted perennials. Arsenic is primarily a surface sterilant. Only when applied in water-soluble form (sodium arsenite) to very sandy soils does it penetrate deeply enough to kill perennial weeds. Arsenic trioxide, because of its relatively low solubility and also because of fixation on soil colloids of that which does dissolve, remains in the topsoil. Its virtue is its long-lasting toxicity against seedlings in the topsoil. It should

Fig. 21. Bridge on Southern Pacific track cleared of vegetation by soil sterilization.

Fig. 22. Ballast of a feeder line sterilized with white arsenic. Prior to treatment this line was heavily infested with yellow star thistle.

Fig. 23. Spur track in the yards of the Spreckels Sugar Co. at Woodland sterilized with white arsenic. The photograph shows the end of a treated strip and emphasizes the weedy nature of the area.

be mentioned here that seedlings of perennials are like those of annuals—that is, they are susceptible to control by surface-acting sterilants. It is the old, established perennials that require a deep-acting soil sterilant.

Field-scale applications

Irrigation structures. The first field-scale work on this project was done by the U. S. Bureau of Reclamation at the suggestion and under the supervision of the University of California. In some 60 treatments arsenic dust was applied to bridgeheads, cattle guards, and other structures along the Delta-Mendota Canal. These applications were made during January and February, 1950. In November, 1950, a series of tests was made in which arsenic trioxide was applied as narrow strips along the lining of the same canal. These were put on by the University working with the Bureau of Reclamation. During this same winter period further treatments on structures along the canal were made by the Bureau of Reclamation. In the early summer of 1951 inspection proved that the treatments of January and February, 1950, were giving almost complete control of annual weeds. Since the canal traverses range land and relatively new agricultural land, there are not many perennials present; the treatments have proved very satisfactory. Even the treatments of November, 1950, gave excellent control by May, 1951, possibly because of heavy rains during the winter and also because the soils treated tended

Fig. 24. Soil sterilization along the right-of-way of the Southern Pacific mainline through Truckee, Calif. Arsenic trioxide at 1,000 pounds per acre.

Fig. 25. Soil sterilization around a cattle guard on the Delta-Mendota Canal. White arsenic was used. Courtesy Bureau of Reclamation, Region 2.

Fig. 26. White arsenic sterilization along the lining of the Delta-Mendota Canal. Courtesy Bureau of Reclamation, Region 2.

Table 5. Results of Soil Sterilization with Arsenic Trioxide on Railroad Plots between Roseville, California, and Verdi, Nevada. Application by Mechanical Applicator (Three-foot Pushcart). Notes Taken in June, 1951 and 1952

Arsenic form	Date	Plot size	Location	Application	Percentage of control		Notes
					1951	1952	
		feet		pounds per acre			
Dust	Jan. 24, 1951	100 x 6	Roseville yard and overpass, Diamond Match Co.	1,500	80	90	Around buildings
Dust		250 x 6		1,500	95	99	Tow path through overpass
Dust		100 x 50		1,500	50	75	Saltgrass, etc.
Dust	Dec. 5, 1950	123 x 9	New England Mills	1,280	50	95	Tow path
Pellets		153 x 6		1,280	50	98	Tow path
Dust		25 x 25		2,000	90	95	Signal mounds
Dust	Dec. 5, 1950	363 x 3	Colfax yards	1,280	50	90	Tow path
Pellets		291 x 3		1,280	75	98	Tow path
Dust		25 x 25		2,000	85	99	Signal mound
Dust	Dec. 5, 1940	426 x 3	Towle Station	1,280	70	95	Mainline
Pellets		450 x 3		1,280	50	75	Mainline
Dust	Dec. 5, 1950	309 x 3	Yuba Pass	1,000	75	95	Mainline
Pellets		219 x 3		1,000	80	98	Mainline
Dust	Dec. 6, 1950	216 x 3	Soda Springs	1,000	75	95	Mainline; applied on snow
Pellets		186 x 3		1,000	85	99	
Dust	Dec. 6, 1950	159 x 9	Truckee yards	1,000	90	100	Rain during application
Dust	Dec. 6, 1950	163 x 6	1½ mi. west of Verdi, Nevada	1,280	50	99	High, dry locality; light snow in winter
Dust		45 x 9		2,000	50	95	

to be gravelly or sandy. Figures 25 and 26 illustrate sterilization on cattle guards and along the lining on the Delta-Mendota Canal.

Airfield. A second large-scale treatment involved application of about 6 tons of arsenic trioxide along the edges of the flight strips of the University Airport at Davis. This material was spread by means of a converted fertilizer drill that covered an 8-foot strip. Put on in late November, 1950, this arsenic has greatly reduced weed infestation which threatened to break up and ruin the thin oil-gravel pavement that is used to protect the flight strips from invasion by weeds.

Experience at this airport has revealed one serious problem in the use of arsenic trioxide, that is, the persistence of certain arsenic-resistant weeds. Here knotweed (*Polygonum aviculare*) has proved the most difficult to handle. Though literally millions of seedlings of this plant have been killed each year on this sterilized area, each season a few seedlings survive, and, being free of competition, they thrive and grow to a surprising size. One of these plants growing through a small crevice in the pavement may spread to a diameter of 6 to 9 feet, making a dense bush a foot or more thick in the center. The root may be fully one-half inch in diameter, and when the plant dies and disintegrates in the winter this hole provides entry for more plants the next year. Yellow star thistle (*Centaurea solstitiales*) is another weed that tolerates a surprising amount of arsenic. Where these weeds survive the arsenic treatment, spraying with Endothal has kept them in control.

Firebreaks. A third field-scale use of arsenic, the largest so far made, has been the treatment of many miles of fire lines in the mountain regions of California. These include southern California firebreak systems and cleared

Fig. 27. Left, applicator for treating firebreaks with white arsenic. Two men can treat several miles of backfire line in one day; the soil remains sterile for 5 or more years. Right, treated strip showing the thin, even coat of white arsenic. During rainfall the white arsenic is washed into the soil. Even when first applied, it holds no attraction for livestock. Courtesy H. D. Bruce, Calif. Forest and Range Expt. Sta., U. S. Forest Service.

Fig. 28. Left, fire line at edge of northern California railroad right-of-way still bare nine years after treatment with 5 pounds of white arsenic per square rod. Right, it is necessary to spread arsenic by hand where the terrain is too rough for mechanical equipment. This picture was taken 9 years after treatment with between 5 and 6 pounds per square rod of soil. Courtesy U. S. Forest Service.

strips along roads, railroads, and powerlines in both north and south, created to confine fires starting on them to the right-of-way.

Both hand and machine applications have been made, although machine-spreading has accounted for most of the treated mileage. Hand-spreading has generally been confined to spot treatments around individual poles on power lines and to comparatively short, although no less important, stretches of fire line too rough for mechanical spreader operation. Equipment similar to that shown in figure 27 (left) has been used on most of the treated miles.

Wherever erosion is not serious and the soil has remained undisturbed after treatment, the effects of both hand- and machine-spread arsenic have been long lasting. Figure 28 shows two sections of a hand-treated fire line along a railroad right-of-way in northern California nine years after treatment. Five pounds of arsenic per square rod was used. Four pounds of arsenic per square rod spread by machine on a southern California firebreak has been almost equally effective against plant invasion (figure 29). Note the burned vegetation on both sides of this firebreak. The fire occurred about four years after treatment. In spite of the barren strip firefighters were unable to stop the fast-running fire at this point. The vegetation on both sides of—and inside—the treated line has seeded in since the burn. This line was disturbed by heavy traffic during the fire.

Spreading arsenic by hand often results in a heavier application than necessary because hand-spreading cannot give complete ground coverage with as thin a coating as can be obtained with the mechanical spreader. Nearly complete coverage is necessary because of the extremely limited lateral movement of the arsenic.

Some of the reasons uniform coverage with minimum quantities of chemical cannot be achieved with hand-spreading are apparent in figures 28 (right) and 31. In a boulder patch such as that in figure 28 (right), one has to work around each rock, throwing arsenic in under each overhanging edge. The cut slope and a 3-foot uncleared strip at its top (figure 30) were sterilized to eliminate cheatgrass as a fire-prevention measure on this busy mountain highway. Dead grass remained on the uncleared strip until the second year after treatment. After that the ground was bare.

Fig. 29. Heavy traffic by firefighters scuffed up the soil on the treated portion of this southern California firebreak. Even with this disturbance, invasion by perennials 7 years after treatment with 4 pounds of arsenic per square rod has been slight. Courtesy U. S. Forest Service.

Whether chemical or mechanical methods are used, permanent removal of vegetation is not always desirable. Erosion is probably the most costly result of misapplication by either method. Vegetation on the firebreak shown in figure 31 was cleared two years before the picture was taken. Gully erosion has resulted in excessive soil movement over much of the width of this firebreak. This strip, which traverses an area of decomposed granite, is too steep to remain stable when bare without special provision for drainage. Arsenic applied to an area such as this will usually disappear entirely by the fourth year. A few water barriers on this slope would have prevented this damage and made arsenic treatment practical.

Experience on both firebreak and right-of-way sterilization has shown the need for posting the treated ways against damage by bulldozers and motor-patrol graders. These bare strips often provide a convenient path for such equipment, and operators frequently let the blade down just to smooth the way as they go. Since arsenic trioxide becomes fixed in only the very top soil layer, blading invari-

Fig. 30. Treating the cut slope and the 3-foot wide strip at the top along this northern California highway. These areas are being sterilized as a fire-prevention measure. At least two years is usually required to get a bare strip without pre-clearing. Courtesy U. S. Forest Service.

Fig. 31. This southern California firebreak in decomposed granite was too steep for successful sterilization without adequate provision for drainage. Erosion such as this, when once started, is difficult to stop. It is less severe than that which often follows disking or hand-hoeing, for these mechanical operations loosen the topsoil. Courtesy U. S. Forest Service.

taken to apply it on relatively calm days, ably renders the treatment void. Posting the treated strips with appropriate warnings seems to be the only solution, since turnover in both supervisory and operator personnel makes verbal instruction of only temporary value.

When the fine granular form of arsenic trioxide is used, care should be as wind will carry appreciable quantities of the chemical off the treated area. Until the chemical is wetted, it is also susceptible to wind erosion after it is on the ground. Most extensive treatments have, therefore, been carried out in the late fall and spring months between rains. Where work programs have made treatment desirable during the dry season, a light sprinkling of treated strips by tank truck has been equally successful. It is even much better than a very heavy rain immediately following application, as this may wash some of the arsenic away.

Many public agencies and utility corporations are averse to broad-scale use of arsenic. Their attitude stems primarily from its bad reputation established several decades ago by applications of arsenic in the form of sodium arsenite.

Both arsenic trioxide and sodium arsenite are poisonous to all animals if taken internally. While sodium arsenite, however, is salty in taste and attractive to grazing animals, arsenic trioxide is unattractive to them and is therefore not a hazard to them once it is on the soil. No harmful effects from soil sterilization treatments with dry arsenic trioxide have been reported in more than ten years of use.

Arsenic trioxide is only slightly soluble in water and is therefore usually spread on the ground dry.

Buyers of arsenic trioxide for weed control are cautioned against it in solution form. Hydroxide is used to dissolve arsenic trioxide, and this converts it to the dangerous arsenite. Arsenic trioxide should be used dry as dust, dustless powder, or pellets.

THE ANSWERS . . .

Arsenic trioxide is the most economical chemical to use where sterilization of 5 to 10 years' duration is desired. The grade known as gray arsenic, assaying 90 to 95 per cent As_2O_3, is satisfactory for soil sterilization purposes. Here are the conclusions in detail.

Toxicity

In 10 California soils arsenic trioxide was less toxic than soluble sodium arsenite during the first cropping of a soil. By the third cropping its toxicity was at a maximum and equal to that of sodium arsenite. By the sixth it was diminishing.

As with arsenite, arsenic trioxide toxicity was highest in light sandy soils, lowest in heavy clays.

When arsenic trioxide stood in contact with moist soils for 2 to 9 days, no increase in toxicity resulted; after 16 days an appreciable increase could be detected.

In the powdered form arsenic trioxide has little tendency to wet in water. Addition of a wetting agent brings about ready wetting, and in one soil this increased wetting was attended by an increase in toxicity during the first cropping. Added at 0.1 per cent of the dry weight of the arsenic, a sulfonate wetting agent (Tenlo 400) reduced dustiness of the arsenic so that it could be applied with a spreader with less hazard to the operator.

Pelleted arsenic was less toxic than powder in greenhouse trials during the first two croppings. By the third it was equal to the powder.

Tests on combinations of arsenic trioxide and CMU prove that they are not antagonistic, that their toxic effects are additive, and that the combination is effective the first year.

Plot trials

Plot trials with arsenic trioxide confirmed the lack of toxicity during the year of application. They emphasized the fact that where perennial weeds are present an additional soil sterilant of greater solubility and leachability should be incorporated.

On railroad ballast pelleted arsenic was more effective than the powder. The pellets were not moved by the wind from passing trains, and they tended to gravitate into crevices where weed seeds germinate.

Results on a series of plots at various elevations along the Southern Pacific line through the Sierra Nevada mountains correlated with annual precipitation better than with any other variable. High precipitation brings about more rapid action by the chemical.

Arsenic trioxide applications have proved effective for controlling weeds along the lining of irrigation ditches, around cattle guards, bridgeheads and similar structures, and paved airstrips.

Field-scale use

The largest use of arsenic trioxide has been on fire lines in the mountain regions. These include firebreak systems and cleared strips along roads, railroads, and powerlines. Machine application is practical on smooth terrain; hand application has been required in rough, steep, and rocky sites.

Arsenic sterilization on sandy or gravelly soils in steep terrain may result in gully erosion. In such situations provision for adequate drainage should be made.

All arsenic-sterilized strips should be posted to avoid disturbance by grading machinery. Such strips provide convenient routes for travel by such equip-

ment, and often volunteer smoothing breaks the arsenic cover and allows reinfestation.

Powder form or pellets

The dust or powder form is satisfactory if wind action is not excessive.

The operator making the application should protect his hands and face from accumulation of the arsenic dust.

Dustiness of the powdered form of arsenic can be eliminated by incorporating 0.1 per cent by weight (1 pound per 1,000 pounds) of a wetting agent and 0.2 per cent of water. The wetting agent and the water should be thoroughly mixed, then added to the arsenic a bit at a time with thorough mixing.

Arsenic can be pelleted by using a lignin binder and screening to retain particles between 10 and 35 mesh. The binder should be non-hygroscopic and sufficiently water soluble that the pellets melt readily when moistened.

Tests have not been conducted on the palatability and acceptability of arsenic trioxide to animals when wetting agents and pelleting binders are included. Anyone using arsenic with such materials added should run an acceptability test before applying in areas accessible to animals.

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